MEDIUM-FREQUENCY PROPAGATION IN COAL MINES

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ABSTRACT

Medium-frequency (MF) waves can propagate in a coal seam, bounded above and below by conducting rock, in an approximate transverse electromagnetic (TEM) transmission-line mode with the electric field vertical and the magnetic field horizontal. The theory of this coal seam mode is applied to recent MF data for a number of mines in order to classify the propagation characteristic of the mines in a simple way.

When conductors such as rails, trolleylines, or power cables are present in the vicinity of the measurement path, it is found that the magnetic field versus range plots have two distinct regions with very different slopes. This effect is attributed to coupling of the cylindrically spreading coal seam mode to a low-attenuation conductor guided mode. As a result, voice communications range between mobile transmitters can extend several thousand meters. The use of MF for mine communications is discussed.

INTRODUCTION

MF wireless radio satisfies communication needs similar to those met by ultra-high-frequency (UHF)/leaky feeder systems.(1)* However, MF systems make use of existing mine wiring for range extension and do not require the installation of leaky feeder cable in the extensive complex of mine tunnels.

It is known that UHF radio suffers from the severe disadvantages of high losses when communicating around corners and through barricades.(2) UHF signals are confined within the boundaries of mine tunnels. MF signals, on the other hand, travel relatively well through the coal and rock.

* Numbers in parenthesis refer to references at the end of this paper.

MF wireless radio is intended to satisfy the communication needs of roving miners as well as the haulage communication requirements of trackless/trolleyless vehicles. The miners involved are typically section foremen, maintenance workers, ventilation crews, and machine operators. An effective MF radio system would answer the following communication needs:

1. Miners working in basic room-and-pillar sections and in sections with special needs, such as longwalls and sections having full-dimension haulage systems.

2. Miners operating vehicles in mines with trackless and trolleyless haulage systems in which traditional trolley wire carrier systems are not useful.

3. Members of rescue teams during mine rescue operations, thereby removing the need for inconvenient trailing wires.

The underground mining industry's extensive experience with trolley-wire carrier-phone systems has shown that a mine's electrical wiring, tracks, trolley wires, phone lines, and air lines can be used to carry low-frequency signals throughout underground mines, even to locations some distrance from the trolley wire-rail haulage system. Early in 1975 the Bureau of Mines bought and tested underground some prototype 335-kHz portable transceivers that were manufactured in South Africa. The wireless communication ranges obtained with these units were quite good and, in fact, much greater than originally anticipated from theoretical predictions. However, the tests left some doubt as to whether 335 kHz was the most favorable operating frequency for U.S. mines.

To better define MF communications technology, the Bureau of Mines initiated a measurements and hardware development program. Its output would be a MF unit to meet the portable wireless communication needs that remained unsatisfied by UHF radio. To be successful it is necessary to determine which operating frequencies are best suited to wireless applications in U.S. room-and-pillar coal operations and to design associated portable equipment rugged and small enough for use by the mining industry.

PROPAGATION MEASUREMENTS AND EXPERIENCE IN COAL MINES

The initial set of comprehensive measurements were made in a conductor-free area of Consolidation Coal's Ireland mine in the Pittsburgh seam. A 60- to 2,000-kHz frequency range was covered. An analysis of the data showed the following:

1. Longer communication ranges than anticipated were achieved (up to 500 m) in conductor-free areas.

2. Maximum ranges occurred at higher frequencies than expected (between 300 and 900 kHz).

3. Propagation was not influenced by the network of tunnels in the coal seam.

4. The best performance occurred when the planes of the loop antennas were oriented vertically and parallel to each other.

Subsequent measurements at other mines have shown that propagation in conductor-free areas is strongly dependent on coal seam properties. Figure 1 shows the results of measurements in six coal seams and clearly demonstrates the wide variation in propagation loss from seam to seam.

Original work indicating the existence of a low attenuation mode in a coal seam was published in 1976 by J. R. Wait.(3) Further analysis has been recently done by A. G. Emslie and R. L. Lagace(4) in which the coal seam is treated as a waveguide propagating a TEM wave. The model assumes the mine can be represented as three layers consisting of coal bounded by rock overburden and underburden and has shown good agreement between theory and experiment in the frequency range of 100 to 1,000 kHz.

OPERATING FREQUENCIES IN CONDUCTOR-FREE AREAS

The data analysis and theoretical modeling of coal seam waveguide radio wave propagation presented above provides a firmer foundation than previously available on which to base the selection of operating frequencies for wireless mine communication in the MF band. Large variations in signal attenuation rate have been found between the three coal seams investigated which are widely separated geographically. The Pittsburgh seam measured in northern West Virginia was found to be the most favorable, while the Herrin No. 6 seam measured in southern Illinois was found to exhibit extremely high loss.

Figures 2 and 3 show theoretical calculations for received field strength at 200 and 400 m, respectively. The parameter values are the average values deduced from the mine data shown in Figure 1 for the Pittsburgh, Pocahontas, and Herrin seams.

Also plotted on these figures for comparison are magnetic field noise levels versus frequency. These noise levels represent the upper bound envelope of average rms values found in active areas of coal mines and a lower bound noise level representing the intrinsic receiver noise for a narrow band frequency modulated (FM) radio receiver having an intermediate frequency (IF) bandwidth (B) = 12 kHz, noise figure (F) = 6 db, and loop antenna effective turns area (NA) = 1 m^2. The active mine noise levels were taken from data measured at spot frequencies in three coal mines by Bensema, Kanda and Adams(5)(6)(7) of the National Bureau of Standards.

Examination of Figures 2 and 3 reveals that performance is best for the combination of lowest coal conductivity and highest rock conductivity. Increasing coal conductivity increases the shunt loss in the coal seam waveguide, while decreasing the rock conductivity increases the series loss, both of which increase the signal attenuation rate. Furthermore, as this attenuation rate increases, the frequency behavior changes from a broad bandpass filter type of characteristic centered around 1 MHz for low attenuation rates like those found in the Pittsburgh seam, to an increasingly attenuated low pass filter characteristic having a steadily decreasing cutoff frequency as the attenuation rate increases to values like those found in the Herrin No. 6 seam. This trend toward the attenuated low pass filter behavior is, of course, more accentuated for the longer communication ranges, i.e., 40 m versus 200 m.

The most favorable frequencies for communicating these ranges can be estimated by comparing the signal level curves with the noise level curves plotted on each figure. The most favorable operating bands are seen to be those where the slopes of the signal and noise curves are equal or nearly equal. Since the signal curves also represent levels for the largest, intrinsically safe transmit moment, an absolute measure of performance can also be estimated by noting the number of db that the signal level curve lies above the noise level curve at the frequency of interest. For example, moderate performance (occasional message repetitions required) requires that the average rms carrier-to-noise ratio at a FM receiver be at least 10 db or better for the mine noise condition prevailing during the message transmission.

The equivalent receiver noise curve is probably the most representative for communication in conductor-free areas located at least one or two entries (i.e., separated by one or two pillar widths) away from mine electrical conductors carrying high noise currents. On the other hand, the active mine upper bound noise curves most likely give an overly pessimistic view. In this latter instance, these levels occur in the immediate vicinity of high-power machinery and electrical conductors, locations where the signal will also be enhanced by the presence of the conductors. Thus an active area noise curve approximately half way between the two noise extremes is probably more indicative of worst case "conductor-free area" noise levels. These levels are likely to occur in transition regions between conductor-free and conductor-present locations.

Figure 2 reveals that conductor-free area portable-to-portable radio ranges on the order of 400 m will be attainable only in highly favorable, low-attenuation seams like the Pittsburgh seam. Furthermore, the performance will occur only at operating frequencies between about 900 kHz and 2 MHz and under noise conditions approaching the receiver-noise-limited case. In addition, Figure 3 illustrates that conductor-free ranges of 200 m will not be attainable in high-loss seams such as the Herrin No. 6

seam, even at frequencies below 100 kHz and under receiver-noise-limited conditions. The outlook is somewhat improved, but not much, for moderate-to-high-loss seams like the Pocahontas No. 3 seam, where 200 m ranges should be possible over a broad band of operating frequencies between about 150 kHz and 1.5 MHz under receiver noise limited conditions.

On a more positive note, the in-mine measurements of Cory [8] and others have also shown that greatly improved radio communication ranges are obtainable in coal mines when the portable units are located in a tunnel having electrical conductors such as a power cable, pagerphone line, or trolley wire/rail line. Significant range improvements have even been experienced with one and sometimes both of the units located in a tunnel separated by a coal-pillar width from the tunnel with the conductors. In some cases improvements have also occurred with one of the units located in a tunnel separated by two coal pillars from the tunnel having the electrical conductors. Since these conductors are generally located in haulageways and working sections where miners requiring communications are also located, this propagation condition is an important one. Moreover, it is one that may allow the desired radio communication ranges to be achieved and exceeded even in coal seams having high signal propagation attenuation rates. Figure 4 shows data taken in three mines near conductors that illustrate the range-enhancing effect of conductors. Additional data are presently being taken in the vicinity of mine electrical conductors and analyzed to quantitatively model and assess the impact of such conductors on the attainable radio communication range.

HARDWARE DEVELOPMENT

The Bureau is currently developing a MF system for mobile and portable communication capable of covering a small mine using belt haulage and battery-powered vehicles. The overall system is indicated in Figure 5 in which a repeater is used to provide whole-mine coverage from portable to portable and from portable to base. Tentative specifications are shown in Table 1.

An operating system is expected to be completed by the fall of 1979.

SUMMARY

Prototype MF wireless radios have been tested in underground mines representing coal seams of several different conductivities. These tests were conducted as part of the Bureau's program to investigate the propagation characteristics of mines. The test results in the 60- to 2,000-kHz range indicate a conductor-free area propagation range of 150 to 500 m and a range of over 1,000 m in the presence of mine conductors. The range at a specific frequency in conductor-free areas is largely dependent on the conductive properties of the coal and, to a lesser extent, on seam thickness and conductive properties of the surrounding rock; in areas with conductors these properties are much less important.

Further underground evaluation of prototype MF wireless radios for both personnel and vehicular use as well as evaluation of various repeater schemes will be performed in conjunction with propagation measurements.

The results of these equipment tests and propagation loss measurements will be used to improve the design and performance and to determine system design guidelines for future mine wireless radio equipment.

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TABLE 1.--Portable transceiver specifications

Frequency range	300-1000- to 10-kHz steps
Channels	2 transmit, 1 receiver for repeater operation and talk around
Modulation	SSB
Antenna	Detachable loop, bandolier
Power out	1 watt PEP
Squelch	Self-adjusting relative to noise background
Weight	Less than 1 kg

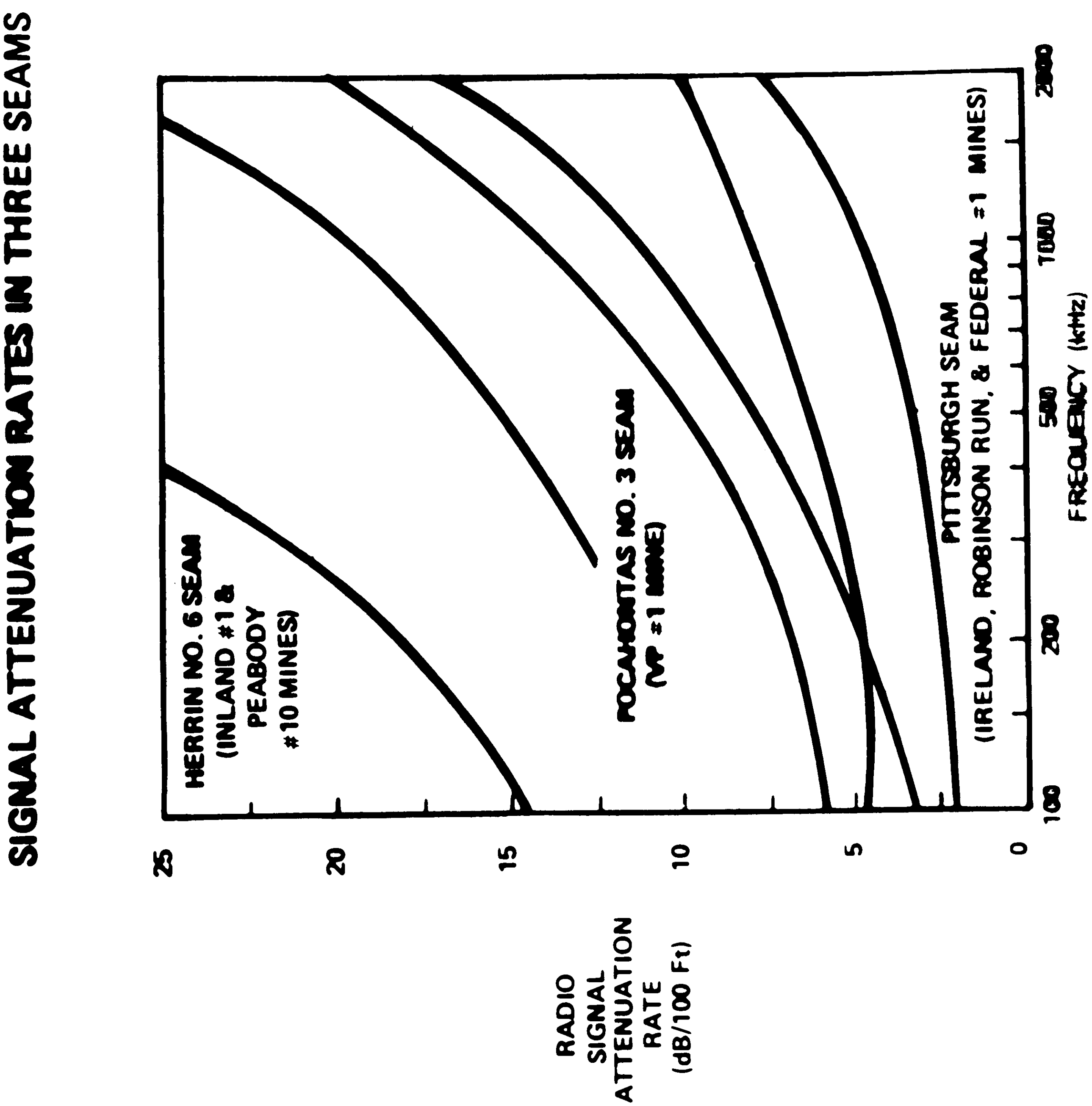

FIGURE 1.--Composite plot of signal attenuation rates in db/100 ft for six mines in three different coal seams

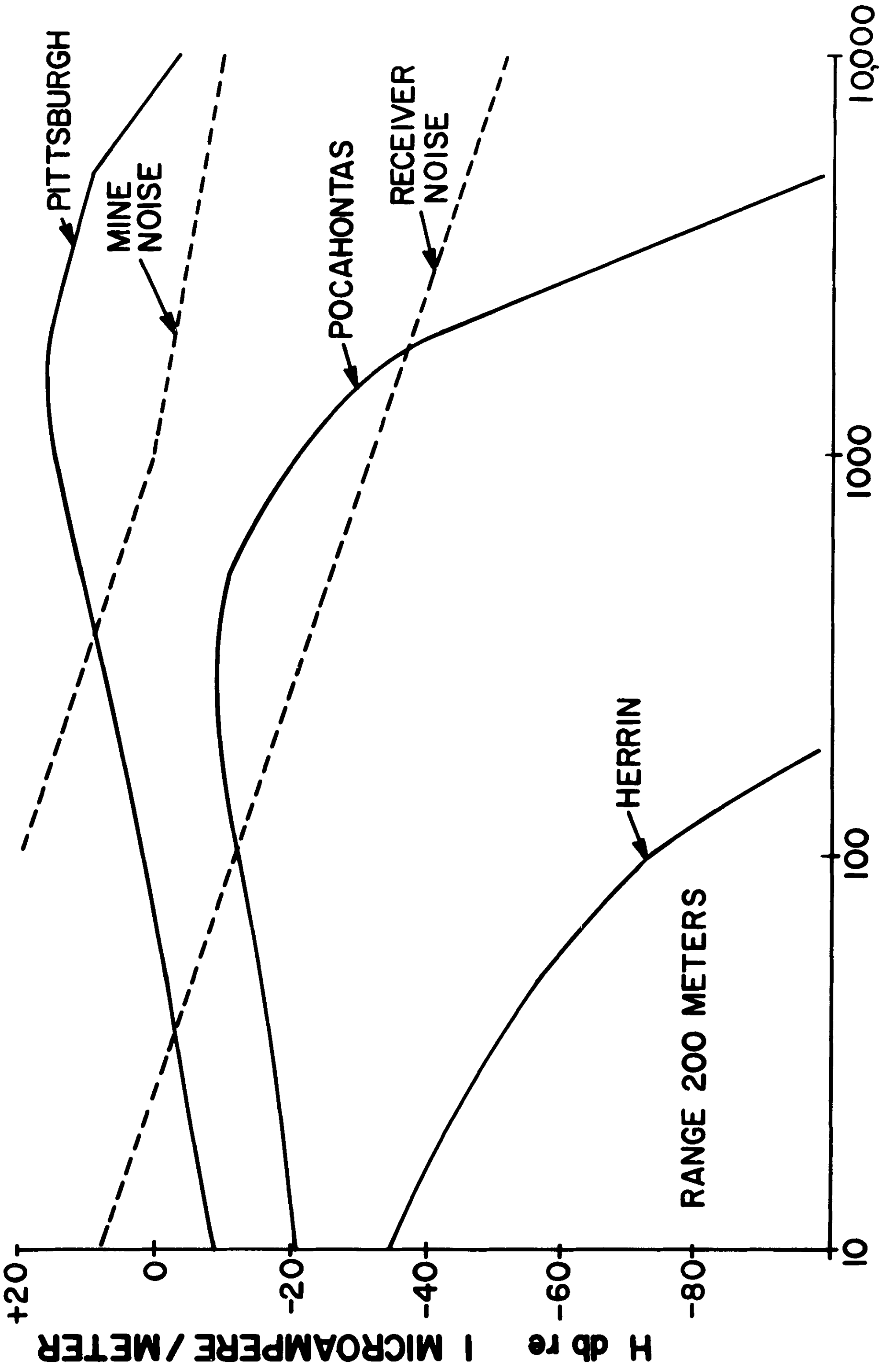

FIGURE 2.--Theoretical values of H as frequency for Pittsburgh, Pocahontas, and Herrin coal seams at a range of 200 m

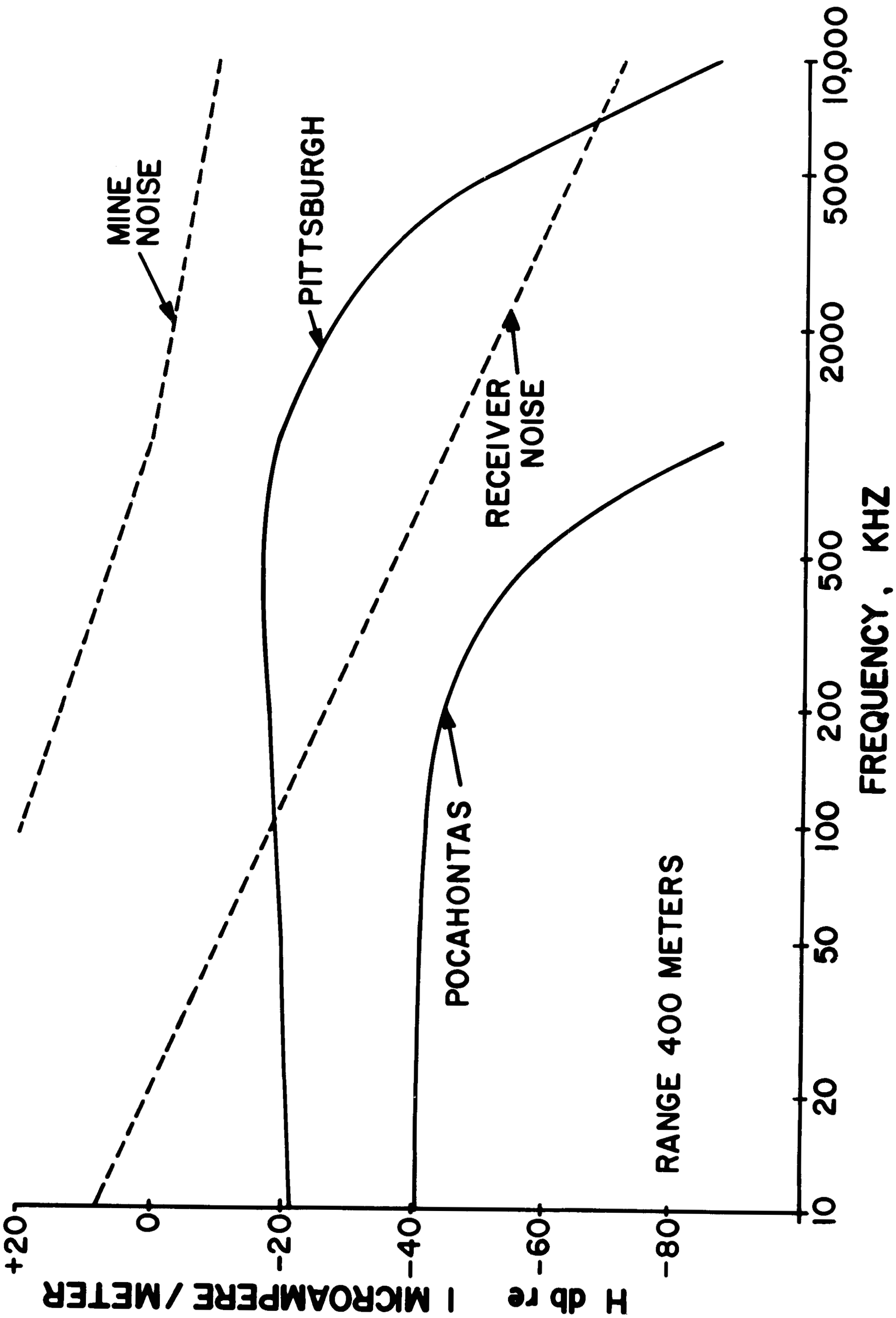

FIGURE 3.--Theoretical values of H vs frequency for Pittsburgh, Pocahontas, and Herrin coal seams at a range of 400 m.

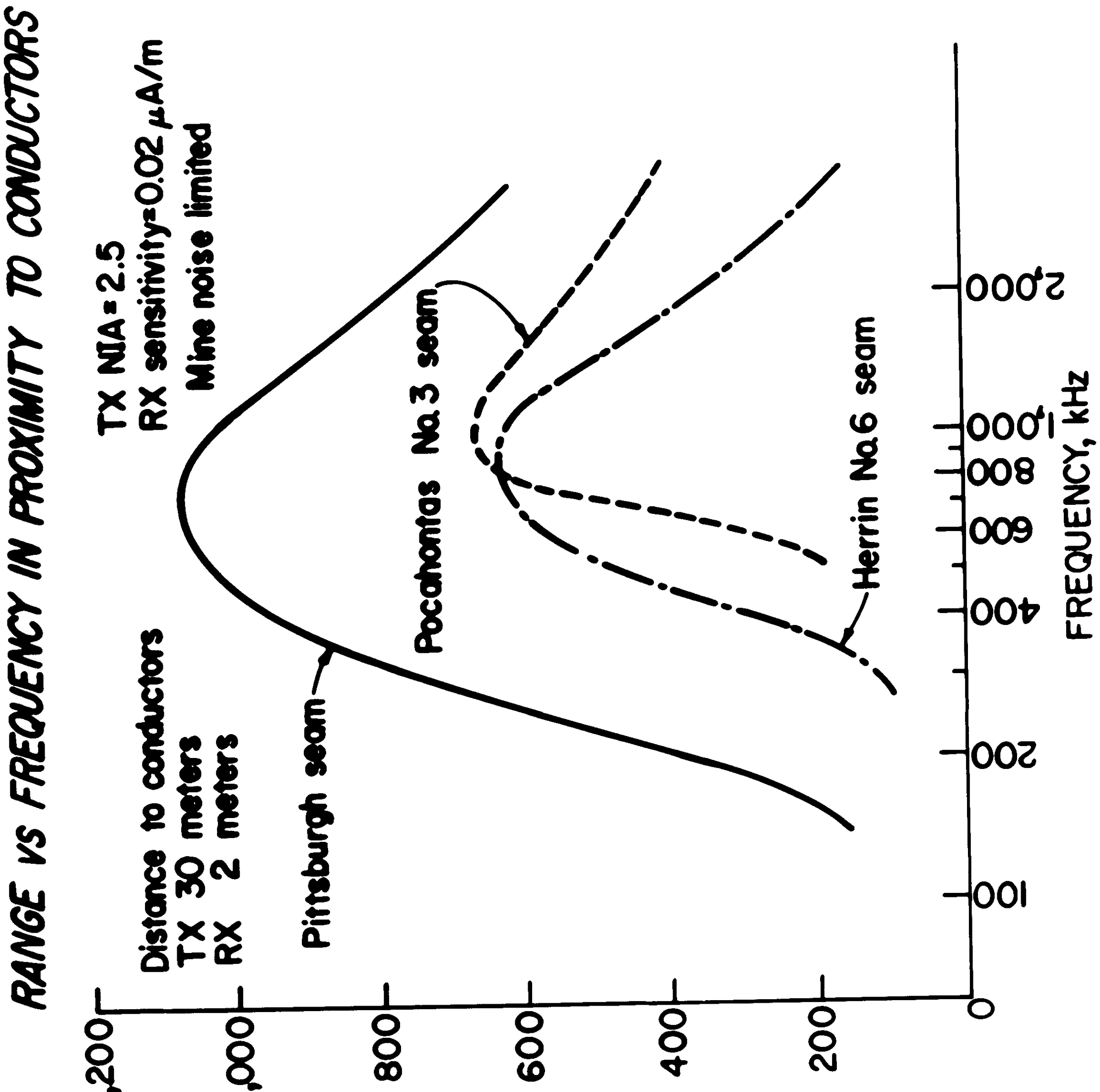

FIGURE 4.--Communication range in three seams in areas with conductors

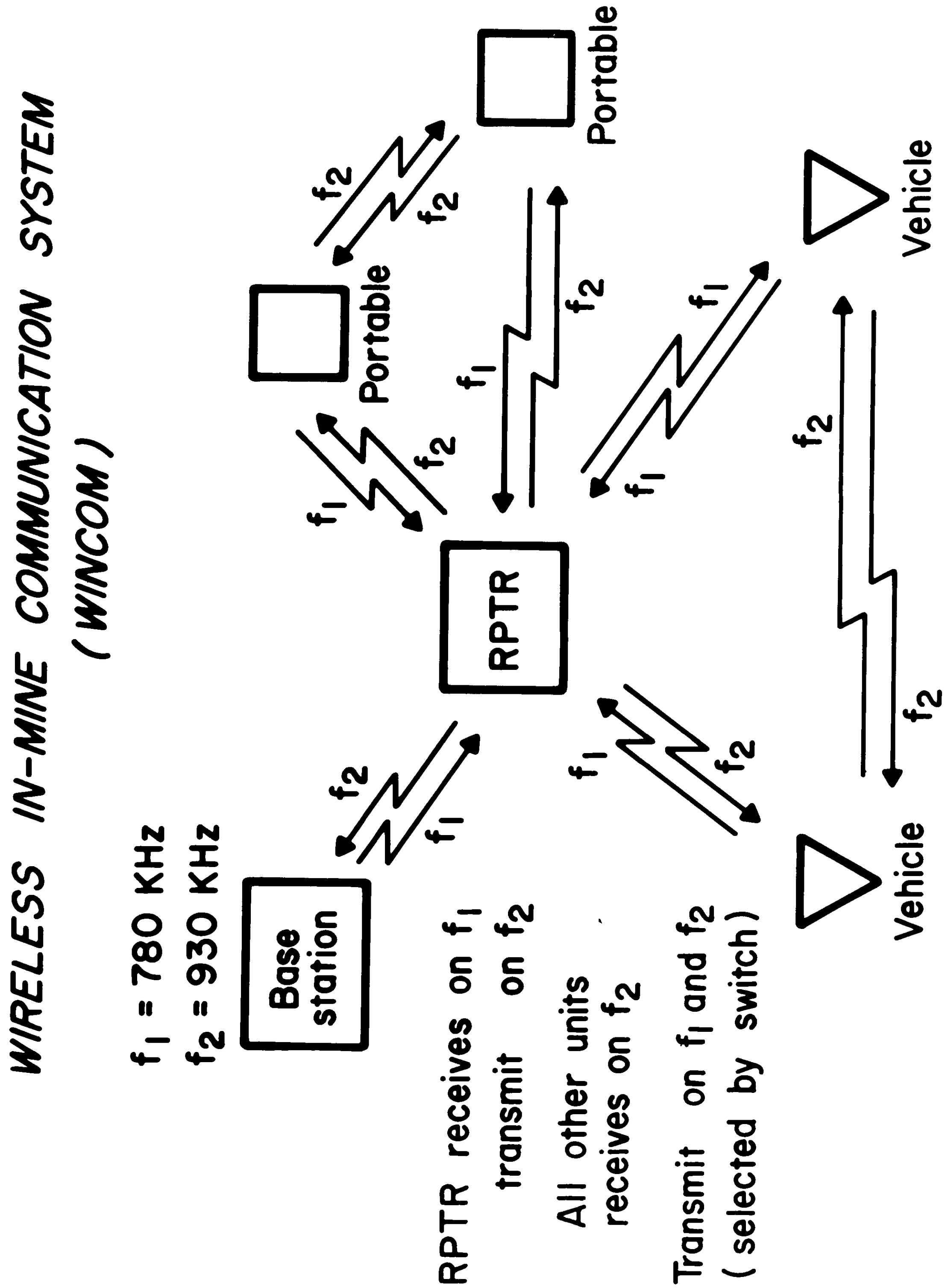

FIGURE 5. Medium-frequency communications using a repeater